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ANALYSIS OF THE COLOR OF GLASS PRODUCTS

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It is pointed out that the quantitative determination of glass color is an important current issue and variants of color measurement are examined.

Glass production is increasing. Both the consumer properties of glass products and the applications of glass have expanded. This especially concerns construction. Since the technology which has taken a large step forward has made it possible to give sheet glass many new useful properties and diversify its external appearance, it is now widely used in construction not only as light-transmitting elements in the walls of buildings but also as a basis for structural and (or) facing, decorative materials. This also concerns the unique creations of acknowledged leaders of modern world architecture, such as, for example, Norman Foster, whose favorite materials are glass and steel, and numerous common structures, including offices and homes, pools, greenhouses, and so forth.

The wide use of glass on building facades raises the question of the color of the glass, including the sameness of the color of the glass sheets used (panels). Architects and customers ordinarily do not like visible sections with different color tone on a facade, especially when the glazed areas are large. Consequently, the problem of quantitative determination and measurement of glass color is an urgent current problem.

But, before approaching the solution of this problem, we must consider how humans perceive glass color. Color perception can be subjective and is associated with individual receptivity. In addition, observation conditions influence how a color appears. For example, the following factors are important when viewing the exterior of the building from the outside:

lighting (i.e. dark, cloud-covered sky can cause the appearance of a color difference which is not noticed under a direct solar illumination);

distance and angle of observation (the color of solar-protected class with a highly selective reflective coating changes as a function of the angle of observation, so that color can be correctly assessed visually only when observing from the same distance and under the same angle of not more than 45° to the normal direction);

the type and color of frames and decorative transoms used on a facade;

the distance between two neighboring glass panels (the angle of view depends on the distance);

the observer's eye;

internal conditions (for example, a lack of illumination in the building: darkness can intensify the perception of a color difference);

external conditions (for example, the presence of other buildings, which can be reflected in glass).

Thus, since the visual perception of color always contains an element of subjectivity, it is important to determine color quantitatively, eliminating this subjectivity. In other words, for objective assessment the color of a product (object) must be "measured" using instruments and expressed quantitatively. Color measurement reduces to determining the numerical value of color coordinates in a prescribed color space or by measuring on a spectrophotometers the characteristics of reflection or transmission of an object and then converting the data obtained in two color coordinates taking account of the function of a standard observer and the type of light source, or to direct measurement of the color coordinates using special instruments — colorimeters.

If different objects (articles) have the same color coordinates, then their color will be the same and this will make it possible for the manufacturer to monitor clearly and guarantee the quality of the manufactured products and to eliminate or provide the possibility of objectively resolving conflicts (disputes) which arise between the manufacturer and consumer when the color of a finished article is visually perceived directly at its place of use.

It is well-known that color is a three-dimensional quantity, and to reproduce any color encountered in nature it is necessary to mix in definite proportions any three linearly independent (monochromatic) colors, called primary colors (in

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addition, these three colors can be real or imaginary; it is important that no color can be obtained by adding any two of the other colors). The numbers of the primary components required to reproduce a given color are called the coordinates of the color [1 – 3].

To determine color accurately and express it numerically the CIE (CIE is the international designation of the International Commmission on Illumination) has adopted different color spaces (color scales) and methods for calculating color coordinates in them.

In colorimetry the most widely used space, which was adopted in 1931, is the *XYZ* space [4]. It is represented by imaginary colors, close to red, green, and blue.

In this colorimetric space, each color is represented by a point with three coordinates: X, Y, and Z. The coordinates of a color X, Y, Z are calculated according to expressions [1 – 4] in which the spectral characteristics (transmission or reflection) of a sample, the spectral density of the radiation of a standard light source, the specific coordinates of light for a CIE standard colorimetric observer (a function of the addition colors), and the width of the wavelength interval are taken into account. These functions determine quantitatively the sensitivity of the conical receptors of an average observer to red, green, and blue light. They have been established experimentally for angles of view 2° (1931) and 10° (1964). In accordance with GOST 7721, several types of sources which reproduce various conditions of illumination are used as the light source:

type A (2856 K) — artificial electric incandescent lamps;

type B (4874 K) — direct sun light;

type C (6774 K) — scattered daylight;

type D65 (6504 K) — average daylight (this is the most widely used type of source).

The working colorimetric system *XYZ* is constructed so that only one coordinate Y determines the quantitative characteristic of a color — the brightness (or lightness). The color coordinate Y is numerically equal to the light transmission or reflection coefficient of the sample whose color is being determined.

So-called chromaticity coordinates x, y, and z, which are relative characteristics, are used as the quantitative characteristic of a color. The coordinates are driven by the relations

$$x = X/(X + Y + Z);$$

$$y = Y/(X + Y + Z);$$

$$z = Z/(X + Y + Z).$$

Since $x + y + z = 1$, a two-dimensional space is sufficient to determine the chromaticity of objects. Objects with the same x and y but different Y are characterized by the same chromaticity but different brightness and, conversely, objects with different x and y but the same Y will be the same with respect to brightness but different with respect to chromaticity. Examples of objects with the same chromaticity but different brightness are glasses with the same composition but different thickness. For example, ordinary transparent sheet glass with thickness 4 mm is characterized by chromaticity parameters $x = 0.312$ and $y = 0.33$ and color coordinate Y (light transmission) = 90, but the color coordinate of the same glass with thickness 2 mm and the same chromaticity coordinate is $Y = 91$ (the calculation was performed for a D65 source and angle of view 2°), while for a 3 mm glass $Y = 90.5$.

TABLE 1.

Coordinate*	According to reflection from the film side	According to reflection from the glass side	According to transmission
X	30.16	17.63	32.39
Y	32.38	20.47	34.66
Z	62.53	20.16	33.40
x	0.24	0.30	0.32
y	0.26	0.35	0.34

* For a D65 source, angle of view 2°.

It should be noted that since the transmission and reflection characteristics of glass (just as any other material) are different, the color of the same object seen “in transmission” and in the reflected variant will be different; the values of the color coordinates calculated according to the transmission and reflection spectra of this sample will also be different. As an example, we present the colorimetric parameters of glass with a reflective coating (D65 source, observation and go to degrees) — a green classic (Table 1).

Of course, objects can be compared and monitored according to color only according to the color characteristics calculated either according to transmission only or according to reflection only from the corresponding side (calculations must also be performed for identical light sources in the same angles of view). This also concerns the color coordinates obtained directly with colorimeters, whose design also permits recording either radiation transmitted through or reflected by a sample.

Since it is difficult to understand the color of an object from the *XYZ* values themselves, the CIE developed other color, more uniform (linear), scales in order to approximate more closely how humans perceive color and also to simplify the understanding and improve the transmission of color differences.

At the present time, one of the most popular color spaces for measuring the color of an object, and most widely used in different fields, is the color space $L^*a^*b^*$ (also designated as CIELAB) adopted by CIE in 1976 (GOST 7721–89). It provides a procedure for assessing in a unified manner color differences in accordance with visual differences and, moreover, it permits determining color quantitatively.

This colorimetric system is a three-dimensional color space, in which each color is represented by a point with

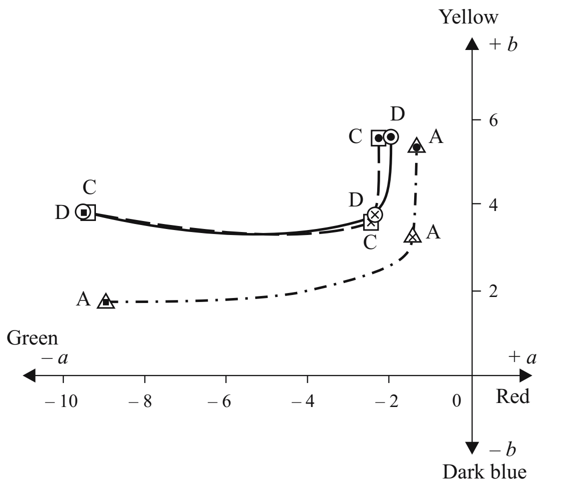

Fig. 1. The values of a^* and b^* form glass with a coating (standard observer, angle of view 2°): ●) according to transmission; ✕ and ■) according to reflection from the film and glass sides, respectively; ○, □, and △) light sources D65, C, and A, respectively.

three coordinates: L^*, a^*, and b^*, where L^* indicates the brightness and a^* and $b^*$are the chromatic coordinates. Positive values of a^* indicate red dominance and negative values green dominance, while positive values of b^* indicate yellow dominance and negative values blue dominance. The center is achromatic (i.e., neutral).

Color coordinates in the system $L^*a^*b^*$ are calculated on the basis of the values of the coordinates in the XYZ system (GOST 7721–89, ISO 7724-1:84) [1 – 3]. The color parameters of glass with a reflective coating, for which the data were presented above in the XYZ system, are given in Table 2. In this case the corresponding values are also indicated for different light sources.

As one can see, although the differences are not so great according to the brightness L^*, they are very significant according to the parameters (a^*, b^*). Since the color of objects is represented more graphically in this system, we shall present the color coordinates in this system of coated glass, whose parameters in the XYZ system were given above, in a graphical variant in the two-dimensional space a^*b^*, because the differences with respect to brightness are not so large. Figure 1 displays the coordinates corresponding to transmission and reflection from both sides and for different sources.

TABLE 2.

Coordinate	According to reflection from the		According to transmission
	film side	glass side	
D65 source, angle of view 2°			
L^*	63.66	52.36	65.48
a^*	– 2.30	– 9.52	– 1.97
b^*	3.75	3.88	5.61
C source, angle of view 2°			
L^*	63.65	52.32	65.48
a^*	– 2.34	– 9.46	– 2.15
b^*	3.69	3.86	5.59
A source, angle of view 2°			
L^*	63.65	51.61	65.69
a^*	– 1.32	– 8.98	– 1.35
b^*	3.33	1.71	5.45

The examples presented above show convincingly how important it is to give the color parameters of the initial materials taking account of the fact that in practice these materials will be observed in transmission, in reflection, and under some predominant illumination.

The color difference (or its absence) of samples in the systems XYZ and $L^*a^*b^*$ is determined quantitatively according to the difference of the corresponding parameters ΔX, ΔY, ΔZ or ΔL^*, Δa^*, Δb^*:

$$\Delta X = X_{\text{sample 2}} - X_{\text{sample 1}};$$

$$\Delta Y = Y_{\text{sample 2}} - Y_{\text{sample 1}};$$

$$\Delta Z = Z_{\text{sample 2}} - Z_{\text{sample 1}};$$

$$\Delta L^* = L^*_{\text{sample 2}} - L^*_{\text{sample 1}};$$

$$\Delta a^* = a^*_{\text{sample 2}} - a^*_{\text{sample 1}};$$

$$\Delta b^* = b^*_{\text{sample 2}} - b^*_{\text{sample 1}}.$$

In the practice of colorimetric measurements in the system $L^*a^*b^*$ it is sometimes customary to indicate the magnitude of total color difference ΔE^*, which is the standard deviation of the values ΔL^*, Δa^*, and Δb^* (GOST 7721–89):

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}.$$

But this parameter is not always an absolute criterion of color differences. This is evident in the following example. Simple 1 has with respect to a standard the difference of the parameters (delta) $\Delta L^* = 0.57$, $\Delta a^* = 0.57$, and $\Delta b^* = 0.57$ and visually agrees well with it, but sample 2 visually differs substantially from the standard (less green) and is characterized by the following delta values: $\Delta L^* = 0.0$, $\Delta a^* = 1.0$, and $\Delta b^* = 0.0$, i.e., for it all differences are associated with the parameter a^*. Nonetheless, the value of ΔE^*_{ab} is the same for both samples:

sample 1:

$$\Delta E^*_{ab} = [(0.57)^2 + (0.57)^2 + (0.57)^2]^{1/2} = 1;$$

sample 2:

$$\Delta E^*_{ab} = [(0.0)^2 + (1.0)^2 + (0.0)^2]^{1/2} = 1.$$

Therefore, the parameter ΔE^*_{ab} cannot always be used as the only criteria, and for greater reliability, besides this pa-

rameter, the values of the coordinates L^*, a^*, b^* themselves should be taken into account. The choice of criterion depends on the form of the product and the requirements which it must meet and is determined by the manufacturer (individually). Thus, the European Association of Manufacturers of Sheet Glass (GEPVP) considers that the parameter ΔE^*_{ab} does not adequately represent color differences, and in the requirements for admissible color differences it confines itself only to the limiting values of ΔL^*, Δa^*, and Δb^* [5]. At the same time, in the American standard ASTM Standard C 1376-03 it is precisely the parameter ΔE^*_{ab} that is used to assess color differences for coated glasses.

Since the type of colorimetric system is not regulated by state standards, the choice of one or another system remains at the discretion of the manufacturer. But we note that although the system $L^*a^*b^*$ is more "graphic," its application presumes that X, Y, Z are calculated first and then the results are converted to the parameters L^*, a^*, b^*, respectively. The large number of calculations increases the effort involved and can result in an additional increase of errors, although this is not as noticeable for manufacturers who have modern equipment with computers. In addition, there also exist colorimeters which give the results immediately in the coordinates $L^*a^*b^*$. Consequently, all nuances must be taken into account when choosing a system.

The maximum admissible differences between the parameters of a sample which are chosen as criteria and the parameters of a standard are given on the basis of a preliminary special visual assessment of the color of the samples and a standard for each type of glass product and can differ depending on their intended purpose. The specific tolerances in the cases where "pass/fail" is used as a criterion, and the statistics of the measurements performed, are a subject of a separate analysis for the specific type of product. We emphasize once again that for accurate and correct colorimetric measurements and calculations it is necessary to work in a unified color space, with a single standard type of radiation source, and with a single standard observer with angle of view 2° or 10°; their choice also depends on the specific case (for large areas of view, which is typical for construction glass, a standard observer with angle of view 10° is recommended for best agreement with the average visual assessments).

Finally, to obtain accurate and correct colorimetric parameters it is necessary to perform spectral measurements with the lowest possible error and perform a calculation with a small step $\Delta\lambda$. The values of $\Delta\lambda$ are ordinarily 5 or 10 nm, depending on the required measurement accuracy and the type of spectral characteristic of a sample. When selective bands are present in the spectral curve, the accuracy depends especially on the value of $\Delta\lambda$, and the smaller this value, the higher the accuracy is.

In closing, we note that the need for switching completely to unified, reliable, and objective numerical criteria for color assessment concerns not only glass for construction but also most types of glass products, including glass containers.

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